

# Neutrino Physics: Theory and Phenomenology

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Various issues in neutrino phenomenology are reviewed, including: the possibility of large mixing angles in various models for neutrino masses, difficulties for degenerate neutrinos as candidates for hot dark matter, strategies for discriminating between different oscillation interpretations of the atmospheric and solar neutrino anomalies, the programme of work for long-baseline neutrino experiments, and the possible future option of a muon storage ring as a neutrino factory.

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## 1. Limits and Indications on $\nu$ Oscillations

The discovery of neutrino masses or oscillations would take particle physics beyond its Standard Model, and therefore requires very stringent standards of proof and verification. Moreover, neutrino experiments are difficult, and their history is littered with unconfirmed claims. Therefore, one must be cautious in accepting new experimental results, and should demand that they fulfil stringent credibility criteria. In my personal view [1], these should include confirmation by more than one experiment, using more than one technique.

These criteria are obeyed by solar neutrino experiments, since five experiments (Homestake, Kamiokande, SAGE, GALLEX, Super-Kamiokande) see a deficit using  $3\frac{1}{2}$  different techniques (Cl, H<sub>2</sub>O, Ga with two extraction schemes) [2]. Now they are also obeyed by atmospheric neutrino experiments: five experiments (Kamiokande, IMB, Super-Kamiokande, Soudan II, MACRO) see anomalies using two different classes of technique (H<sub>2</sub>O, tracking calorimetry) [2]. Therefore, I take these results very seriously as evidence for new physics. On the other hand, only one accelerator experiment (LSND) sees an anomaly [3], using *a fortiori* just one technique (liquid scintillator). Therefore, I prefer to adopt a wait-and-see attitude to this result, eagerly awaiting its confirmation by another experiment such as KARMEN or MiniBooNE [2].

In the general perception, the case for atmospheric neutrino oscillations has recently leap-frogged over that of solar neutrinos. This is largely because, in addition to the sheer number of experiments reporting  $\nu_\mu$  deficits, the Super-Kamiokande Collaboration has reported dramatic effects in the zenith-angle distributions [4], where many systematic

errors cancel [5]. Moreover, both low- and high-energy data show compatible effects, indicating that the  $\nu_\mu/\nu_e$  ratio decreases as  $L/E$  increases, just as expected if  $\nu_\mu$  oscillate into  $\nu_\tau$  or perhaps a sterile neutrino  $\nu_s$ .

In the case of solar neutrinos, the overall deficit has been confirmed by Super-Kamiokande with higher statistics [6], but no comparable “smoking gun” for neutrino oscillations has yet appeared. There is a hint of a day-night difference [6], but its significance remains below two standard deviations, and there is also a hint of an distortion of the energy spectrum [6], but a constant suppression is still compatible with the data at the few-percent confidence level.

Before launching into the theory of neutrino masses, it is useful to review why the oscillation hypothesis is being pursued to the exclusion of other possible explanations. In the case of atmospheric neutrinos, most neutrino decay scenarios are excluded [7], flavour-changing interactions with matter are highly disfavoured [8], and violations of Lorentz invariance and the Principle of Equivalence are disfavoured by the pattern of zenith-angle distributions at low and high energies [9]. In the case of solar neutrinos, the standard solar model is strongly supported by the helioseismological data [10], which do not allow substantial changes in the solar equation of state, and previous claims of a time dependence associated with the solar cycle have not been established.

## 2. Neutrino Masses

If these are non-zero, they must be much smaller than those of the corresponding charged leptons [11]:

$$m_{\nu_e} \lesssim 2.5 \text{ eV} , \quad m_{\nu_\mu} \lesssim 160 \text{ keV} , \quad m_{\nu_\tau} \lesssim 15 \text{ eV} , \quad (1)$$

so one might think naively that they should vanish entirely. However, theorists believe that particle masses can be strictly zero only if there is a corresponding conserved charge associated with an exact gauge symmetry, which is not the case for lepton number. Indeed, non-zero neutrino masses appear generically in Grand Unified Theories (GUTs) [12]. However, it is not necessary to postulate new particles to get  $m_\nu \neq 0$ : these could be generated by a non-renormalizable interaction among Standard Model particles [13]:

$$\frac{(\nu_L H)(\nu_L H)}{M} \quad (2)$$

where  $M \gg m_W$  is some new, heavy mass scale. The most plausible guess, though, is that this heavy mass is that of some heavy particle, perhaps a right-handed neutrino  $\nu_R$  with mass  $M \sim M_{GUT}$ .

In this case, one expects to find the characteristic see-saw [14] form of neutrino mass matrix:

$$(\nu_L, \nu_R) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \quad (3)$$

where the off-diagonal matrix entries in (3) break  $SU(2)$  and have the form of Dirac mass terms, so that one expects  $m = 0(m_{\ell,q})$ . Diagonalizing (3), one finds a light neutrino mass

$$m_\nu \simeq \frac{m^2}{M} \quad (4)$$

Choosing representative numbers  $m \sim 10$  GeV,  $m_\nu \sim 10^{-2}$  eV one finds  $M \sim 10^{13}$  GeV, in the general ballpark of the grand unification scale.

The past year has witnessed tremendous activity in the theoretical study of neutrino masses [15], of which I now pick out just a few key features:

*Other light neutrinos?*: we know from the LEP neutrino-counting constraint:  $N_\nu = 2.994 \pm 0.011$  [16], that any additional neutrinos must be sterile  $\nu_s$ , with no electroweak interactions or quantum numbers. But if so, what is to prevent them from acquiring large masses:  $m_s \nu_s \nu_s$  with  $m_s \gg m_W$ , as for the  $\nu_R$  discussed above? In the absence of some new theoretical superstructure, this is an important objection to simply postulating light  $\nu_s$  or  $\nu_R$ .

*Majorana masses?*: most theorists expect the light neutrinos to be essentially pure  $\nu_L$ , with only a small admixture  $\mathcal{O}(m/M)$  of  $\nu_R$ . In this case, one expects the dominant effective neutrino mass term to be of Majorana type  $m_{eff} \nu_L \nu_L$ , as given by (2) or (3).

*Large mixing?*: small neutrino mixing used perhaps to be favoured, by analogy with the Cabibbo-Kobayashi-Maskawa mixing of quarks. However, theorists now realize that this is by no means necessary. For one thing, the off-diagonal entries in (now considered as a  $3 \times 3$  matrix) (3) need not be  $\propto m_q$  or  $m_\ell$  [17]. Then, even if  $m \propto m_\ell$ , we have no independent evidence that mixing is small in the lepton sector. Finally, even if  $m$  were to be approximately diagonal in the same flavour basis as the charged leptons  $e, \mu, \tau$ , why should this also be the same case for the heavy Majorana matrix  $M$  [17]?

Since  $\sqrt{\Delta m_{atmo}^2} \sim 10^{-1}$  to  $10^{-1\frac{1}{2}}$  eV  $\gg \sqrt{\Delta_{solar}^2} \sim 10^{-2}$  to  $10^{-2\frac{1}{2}}$  eV (MSW solution [18]) or  $10^{-5}$  eV (vacuum solution), one may ask whether large neutrino mixing is compatible with a hierarchy of neutrino masses. To feel more comfortable about this possibility, consider the following very simple parametrization of the inverse of a  $2 \times 2$  neutrino mass matrix [17]:

$$m_\nu^{-1} \equiv \begin{pmatrix} b & d \\ d & c \end{pmatrix} = d \begin{pmatrix} b/d & 1 \\ 1 & c/d \end{pmatrix} \quad (5)$$

Diagonalizing this, one finds mixing:

$$\sin^2 2\theta = \frac{4d^2}{(b-c)^2 + 4d^2} \quad (6)$$

which is large if  $|d| \gtrsim |b-c|$ . However, this does not require degeneracy of the two mass eigenvalues:

$$m_\pm = \frac{2}{(b+c) \pm \sqrt{(b-c)^2 + 4d^2}} \quad (7)$$

since a large hierarchy can be obtained if  $d^2 \sim bc$ . We see in Figs. 1, 2 [17] that large mixing  $\sin^2 \theta \gtrsim 0.8$  and a hierarchy  $m_+/m_- \gtrsim 10$  of neutrino masses can be reconciled for “reasonable” values of the dimensionless ratios in (5), e.g.,  $b/d \sim 0.5$ ,  $c/d \sim 1.5$ . However, it would be difficult to accommodate the extreme hierarchy required by the vacuum solution to the solar neutrino deficit in such a naïve approach.

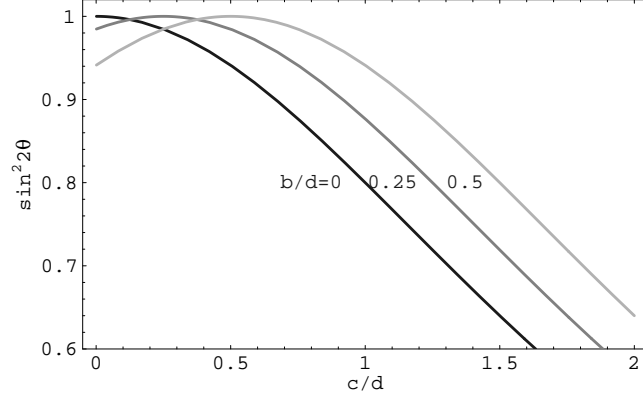


Figure 1. *Dependence of the neutrino mixing angle in the simple two-flavour model (5): note that one may find  $\sin^2 \theta > 0.8$  for generic values of the matrix elements [17].*

There may also be significant enhancement of neutrino mixing by renormalization-group effects between the GUT scale and the electroweak scale [17,20]. The renormalization-group equation for the  $2 \times 2$  mixing angle  $\theta$  is

$$16\pi^2 \frac{d}{dt} (\sin^2 2\theta) = -2(\sin^2 2\theta) (\cos^2 2\theta) (\lambda_3^2 - \lambda_2^2) \frac{m_+ + m_-}{m_+ - m_-} \quad (8)$$

We see that  $\theta$  can be enhanced if either the combination of Yukawa couplings  $(\lambda_3^2 - \lambda_2^2)$  is large or  $(m_+ - m_-)$  is small. Fig. 3 [17] shows an example with large Yukawa couplings corresponding to a large value of the ratio of Higgs vev's  $\tan \beta$  in a supersymmetric model. We see that a renormalization-group enhancement of  $\sin^2 2\theta$  from  $\lesssim 0.2$  at the GUT scale to  $\gtrsim 0.9$  at the electroweak scale is quite possible.

Many theoretical models of neutrino masses are circulating, often based on specific GUT models [19] and/or global U(1) flavour symmetries, which illustrate some of the points made earlier. For example, in a flipped SU(5) model [17], the Dirac neutrino mass matrix

$$m_\nu^D \propto \begin{pmatrix} \epsilon & \mathcal{O}(1) & 0 \\ \epsilon & \mathcal{O}(1) & 0 \\ 0 & 0 & \mathcal{O}(1) \end{pmatrix} \quad (9)$$

in a first approximation, where  $\epsilon$  is small, so that  $m_\nu^D$  is not  $\propto m_q$  or  $m_\ell$ . There are also SO(10) models [22] in which entries in the quark and lepton mass matrices have very different U(1) weightings, so that lepton mixing does not parallel quark mixing. Moreover, in U(1) models it is very natural to find a heavy Majorana mass matrix that is off-diagonal in the  $e, \mu, \tau$  basis. For example, in a  $2 \times 2$  model, if the  $\nu_R^{(i)}$  have U(1) charges  $n_i$ , then the heavy Majorana matrix

$$M_{ij} \sim \epsilon^{n_i + n_j} \quad (10)$$

where  $\epsilon \ll 1$  is a U(1) hierarchy factor. Then, if  $|n_1 - n_2| \ll |n_{1,2}|$ , one finds

$$M_{ij} \propto \begin{pmatrix} 0 & \mathcal{O}(1) \\ \mathcal{O}(1) & 0 \end{pmatrix} \quad (11)$$

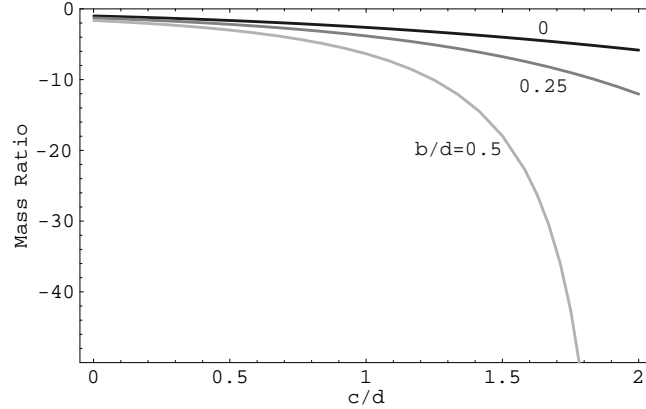


Figure 2. *Dependence of the ratio of neutrino mass eigenvalues on the simple model (5): note that a hierarchy of more than an order of magnitude may be found for generic values of the matrix elements, that may also give large  $\sin^2 \theta$  [17].*

which is a potential source of large neutrino mixing.

In these GUT and U(1) frameworks, near-degeneracy of neutrino masses:  $|m_i - m_j| \ll m_{i,j}$  looks rather implausible, so that one might expect

$$m_3 \sim \sqrt{\Delta m_{atmo}^2} \gg m_2 \sim \sqrt{\Delta m_{solar}^2} \gg m_1 \quad (12)$$

However, there are also models with non-Abelian symmetries [21] which predict degenerate or near-degenerate neutrino masses.

Should one expect more than one large neutrino mixing angle? This seems very likely: for example, in the flipped SU(5) model [17] that yields (9) for the Dirac neutrino mass matrix, one also finds

$$M \sim \begin{pmatrix} X & X & 0 \\ X & 0 & X \\ 0 & X & X \end{pmatrix} \quad (13)$$

for the heavy Majorana mass matrix, where all the non-zero entries  $X$  could be comparable, and plausibly of order  $10^{13 \pm 1}$  GeV, as required by the see-saw mechanism [14]. The small-angle MSW solution would then appear, possibly, to be disfavoured.

Before leaving this section, it is useful to record the general form of the  $3 \times 3$  neutrino mixing matrix [23]:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12}e^{i\delta} - c_{12}s_{13}s_{23} & c_{12}c_{23}e^{i\delta} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{23}s_{12}e^{i\delta} - c_{12}c_{23}s_{13} & -c_{12}s_{23}e^{i\delta} - c_{23}s_{12}s_{13} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (14)$$

which includes two CP-violating Majorana phases  $\alpha, \beta$  as well as three mixing angles  $\theta_{12}, \theta_{23}, \theta_{13}$  and one CP-violating phase  $\delta$  as in the quark case. Thus, a complete programme of neutrino physics should aim at three masses, three mixing angles and three

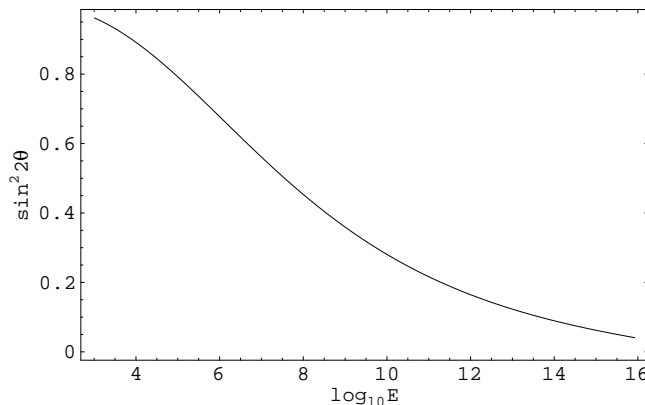


Figure 3. *Example of the possible renormalization (8) of the neutrino mixing angle: note that it may be enhanced to  $\sin^2 \theta > 0.8$  even if it is small at the GUT scale [17].*

phases. So far, we have experimental hints about the possible magnitudes of two mass-squared differences  $\Delta m^2$ , but not the overall neutrino mass scale. One mixing angle seems to be large:  $\theta_{23} \sim 45^\circ \pm 15^\circ$  (?) [4] and one small  $\theta_{13} \sim 0^\circ \pm 20^\circ$  (?) [24], but the magnitude of  $\theta_{12}$  is still unclear, and we have no information about any of the phases. Indeed, the two Majorana phases are essentially unobservable in experiments at energies  $E \gg m_\nu$ , though they do play a role in neutrinoless double- $\beta$  ( $\beta\beta_{0\nu}$ ) decay, as we discuss later.

### 3. Neutrinos as Dark Matter?

Let us set this possibility in context by first reviewing the density budget of the Universe, in units  $\Omega_i \equiv \rho_i/\rho_c$  of the critical density  $\rho_c \sim 10^{-29} \text{ gcm}^{-3}$ . Generic inflation models predict  $\Omega_{total} = 1 + \mathcal{O}(10^{-4})$ , whereas the visible baryons in stars, dust, etc., yield  $\Omega_{VB} \lesssim 0.01$ . The success of Big-Bang Nucleosynthesis calculations [25] suggests that the overall baryon density  $\Omega_B \sim 0.05$ . This is not only  $\ll \Omega_{total}$  but even  $\ll \Omega_m \sim 0.3$ , the total mass density inferred from observations of clusters of galaxies [26]. Therefore the Universe must contain plenty of invisible non-baryonic dark matter.

The astrophysical theory of structure formation suggests that most of the dark matter is in the form of cold non-relativistic particles:  $\Omega_{CDM} \gtrsim 0.2$  [27]. However, this theory does not fit perfectly the combined data on large-scale structure and the fluctuations observed in the cosmic microwave background radiation, as seen in Fig. 4 [28]. One possibility is to supplement cold dark matter with hot dark matter in the form of neutrinos:

$$\Omega_\nu \sim \sum_\nu \left( \frac{m_\nu}{98 \text{ eV}} \right) h^{-2} \quad (15)$$

where  $h$  parametrizes the present Hubble expansion rate:  $H \equiv 100 h \text{ kms}^{-1} \text{ Mpc}^{-1}$ ,  $h \sim 0.7 \pm 0.1$ . However, alternative modifications of the minimal cold dark matter model are possible, such as one with a cosmological constant:  $\Omega_\Lambda \sim 0.7$ , which would be consistent with inflation:  $\Omega_{total} \simeq 1$ , the age of the Universe, and the new data on high-redshift supernovae [29].

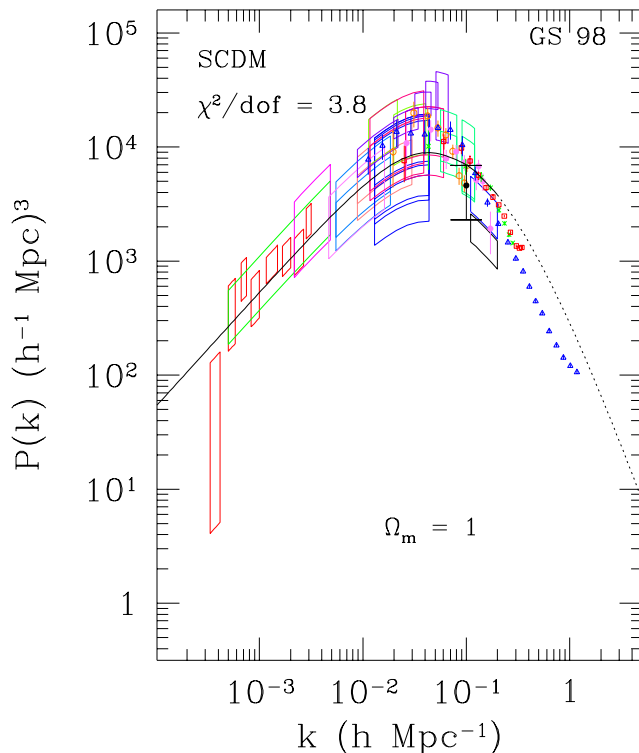


Figure 4. *Comparison of the available data on the power  $P(k)$  in the cosmic microwave background (parallelograms) and on large-scale structure, compared with the standard cold dark matter model (SCDM, solid line) with  $\Omega_m = 1$ : although SCDM reproduces qualitatively the trends seen in the data, it fails at large wave number  $k$  [28].*

The best one can probably say on the basis of present astrophysical and cosmological data is that

$$m_\nu \lesssim 3 \text{ eV}, \quad (16)$$

which is comparable to the direct limit (1) on  $m_{\nu_e}$ . The next generation of astrophysical and cosmological data will probably be sensitive to  $m_\nu \gtrsim 0.3 \text{ eV}$  [30]. Even  $m_\nu \gtrsim 0.03 \text{ eV}$  may be of cosmological importance, but one would need to be very brave to claim astrophysical evidence for a neutrino in the atmospheric neutrino mass range.

Could neutrinos be degenerate, with masses  $\bar{m} \gtrsim 2 \text{ eV}$  and close to the direct and astrophysical limits (1), (16) [31]? Any such scenario would need to respect the stringent constraint imposed by the absence of  $\beta\beta_{0\nu}$  decay [32]:

$$\langle m_\nu \rangle_e \simeq \bar{m} |c_{12}^2 c_{13}^2 e^{i\alpha} + s_{12}^2 c_{13}^2 e^{i\beta} + s_{13}^2| \lesssim 0.2 \text{ eV} \quad (17)$$

In view of the upper limit on  $\nu_\mu - \nu_e$  mixing from the Chooz experiment [24], let us neglect provisionally the last term in (17). In this case, there must be a cancellation between the first two terms, requiring  $\alpha \simeq \beta + \pi$ , and

$$c_{12}^2 - s_{12}^2 = \cos 2\theta_{12} \lesssim 0.1 \Rightarrow \sin^2 2\theta_{12} \gtrsim 0.99 \quad (18)$$

Thus maximal  $\nu_e - \nu_\mu$  mixing is necessary. This certainly excludes the small-mixing-angle MSW solution and possibly even the large-mixing-angle MSW solution, since this is not compatible with  $\sin^2 2\theta = 1$  (which would yield a constant energy-independent suppression of the solar neutrino flux), and global fits typically indicate that  $\sin^2 \theta_{12} \lesssim 0.97$ , as seen in Fig. 5 [33]. Global fits before the new Super-Kamiokande data on the energy spectrum indicated that  $\sin^2 2\theta \sim 1$  was possible for vacuum-oscillation solutions. However, the new Super-Kamiokande analysis of the energy spectrum now indicates [6] that, if there is any consistent vacuum-oscillation solution at all, it must have  $\sin^2 2\theta$  considerably below 1, providing another potential nail in the coffin of degenerate neutrinos.

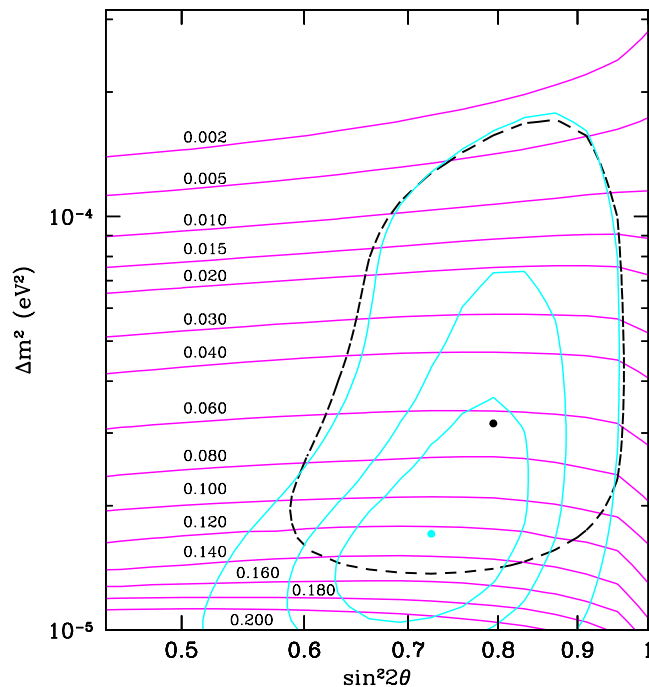


Figure 5. Preferred region of  $\sin^2 \theta$  and  $\Delta m^2$  for the large-mixing-angle MSW solution to the solar neutrino problem, both with (dashed contours) and without (grey contours) the measured day-night asymmetry: note that  $\sin^2 \theta < 0.97$  [33].

The vacuum-oscillation solution would require extreme degeneracy:  $\Delta m \sim 10^{-10} \overline{m}$ , which is impossible to reconcile with a simple calculation of neutrino mass renormalization in models with degenerate masses at the  $m_{\nu_R}$  scale [31], as seen in Fig. 6. Mass-renormalization effects also endanger the large-angle MSW solution (which would require  $\Delta m \sim 10^{-4} \overline{m}$ ), and, in the context of bimaximal mixing models, also generate unacceptable values of the neutrino mixing angles. These renormalization problems may not be insurmountable [34], but they do raise non-trivial issues that must be addressed in models of (near-) degenerate neutrino masses [35].



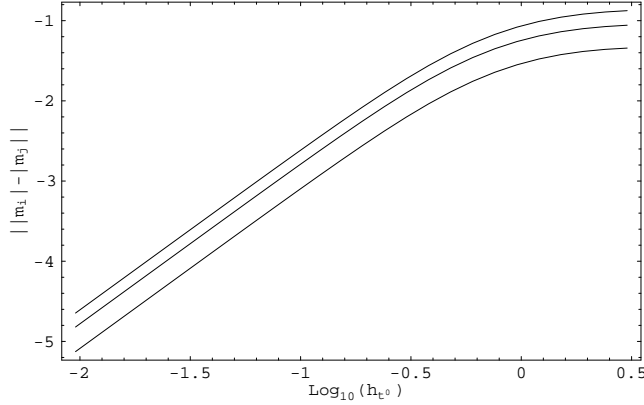


Figure 6. *Renormalization of degenerate neutrino masses as a function of the assumed Yukawa coupling  $h$ : note that the degeneracy breaking is too large, except for very small values of  $h$  [31].*

#### 4. How to Discriminate Between Oscillation Scenarios?

In the case of atmospheric neutrinos, one should consider *a priori* the possibilities of  $\nu_\mu \rightarrow \nu_e$ ,  $\nu_\mu \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_s$  oscillations. The first of these is certainly not dominant, as we have learnt from the Chooz [24] and Super-Kamiokande [4,6] data. However,  $\nu_\mu \rightarrow \nu_e$  oscillations could be present at a subdominant level. Future analyses should use a complete three-flavour framework (14) [36], in which both  $\nu_\mu \rightarrow \nu_e$  and  $\nu_\mu \rightarrow \nu_\tau$  oscillations are allowed. As seen in Fig. 7 [36], the proportion of  $\nu_\mu \rightarrow \nu_e$  oscillations could be quite substantial, particularly for  $3 \times 10^{-3} eV^2 \gtrsim \Delta m^2 \gtrsim 1 \times 10^{-3} eV^2$ .

Several tools to discriminate between dominant  $\nu_\mu \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_s$  oscillations are available. One is  $\pi^0$  production, which is present in  $\nu_\tau$  interactions, but absent for  $\nu_\mu \rightarrow \nu_s$  oscillations. The present data from Super-Kamiokande yield [6]:

$$(\pi^0/e)_{obs}/(\pi^0/e)_{MC} = 1.11 \pm 0.06 \pm 0.26 \quad (19)$$

where the Monte Carlo (MC) assumes oscillations into neutrinos with conventional weak interactions. This ratio would be  $\lesssim 0.7$  for  $\nu_\mu \rightarrow \nu_s$  oscillations. As seen in (19), the data prefer  $\nu_\mu \rightarrow \nu_\tau$  oscillations, and the statistical measurement error is relatively small, but it is not possible to draw any definite conclusion at this stage [6], because of the large systematic error. This arises from uncertainties in the  $\pi^0$  production cross section and the detector acceptance, which should soon be reduced by data from the nearby detector in the K2K beamline, hopefully enabling some definitive conclusion to be drawn.

A second tool is provided by the zenith-angle distributions for atmospheric neutrino events, which differ between  $\nu_\mu \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_s$  oscillations, because of matter effects in the latter case. As we heard here [6], preliminary measurements from Super-Kamiokande tend to disfavour dominant  $\nu_\mu \rightarrow \nu_s$  at the  $2 - \sigma$  level, and it will be interesting to see whether this trend is confirmed.

In the longer run, a third tool will be provided by the neutral-current/charged-current event ratio in long-baseline neutrino experiments, as discussed in the next section.

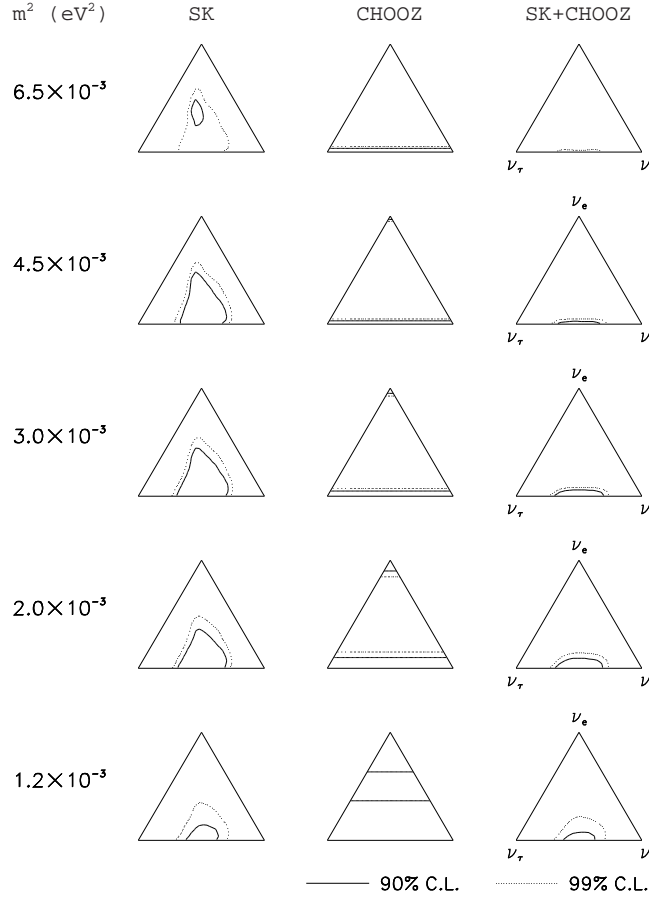


Figure 7. *Three-flavour analysis of atmospheric neutrino data: note that a 10 % admixture of  $\nu_\mu - \nu_e$  mixing cannot be excluded [36].*

In the case of solar neutrinos, there are again three main analysis tools available to Super-Kamiokande to help discriminate between the small- and large-angle MSW and vacuum-oscillation solutions. One is provided by the distortion of the energy spectrum. Even without including the possibility of a big *hep* contribution [37], the large-angle MSW solution is very consistent with the latest Super-Kamiokande data, whereas the small-angle MSW solution is somewhat restricted, and the vacuum-oscillation solution appears almost excluded [6]. This is because the range of  $\sin^2 2\theta$  and  $\Delta m^2$  favoured by the energy spectrum has very little overlap with that favoured by the overall suppression in the rate.

The second tool is the day-night effect, which may also now be showing up close to the  $2 - \sigma$  level [6]. This also restricts the parameter space of both the small- and large-angle MSW solutions. In the former case, a possible signature is an enhancement as neutrinos pass through the Earth's core, which is not apparent in the data. No day-night effect is expected in the case of vacuum oscillations, which may eventually turn into a problem if the current trend is confirmed.

A third tool that may soon supply some discriminating power is the seasonal variation. In the case of the small-angle MSW solution, there should only be a geometric effect, whereas a larger effect could appear in the other two cases, particularly at high energies. Currently there is a hint of a seasonal variation in the Super-Kamiokande data [6], but this is not yet ready to discriminate between the different scenarios.

In the near future, important insight into the solar-neutrino problem will be provided by the SNO measurement of the neutral-current/charged-current ratio. BOREXINO will also provide important input concerning the suppression of intermediate-energy solar neutrinos. Another exciting possibility is offered by the KamLAND experiment, which can probe the large-angle MSW solution directly in a long-baseline reactor experiment. Within a few years, we should find a definitive resolution of the solar neutrino problem. In the case of atmospheric neutrinos, this may require the input from the long-baseline accelerator-neutrino experiments that we now discuss.

## 5. Possible Long-Baseline Accelerator Neutrino Experiments

In the previous sections, we have reviewed the various strong pieces of evidence for possible new neutrino physics beyond the Standard Model, which are certainly highly indicative of neutrino masses and oscillations. However, in the views of many, it is necessary to use the controlled beams provided by accelerators - whose fluxes, energy spectra and flavour contents are known and adjustable - to pin down the interpretation of (in particular) the atmospheric-neutrino data, and to make accurate measurements.

Two long-baseline accelerator-neutrino beams have already been approved. The K2K project extends over 250 km between KEK and the Kamioka mine [38], and has just announced its first event in the Super-Kamiokande detector. This will be joined in 2002 by the 730 km NuMI project sending a beam from Fermilab to the new MINOS [39] detector in the Soudan mine. Under active discussion in Europe is the NGS project [40] to send a neutrino beam from CERN to the Gran Sasso laboratory, also some 730 km distant. This has been recommended by CERN's Scientific Policy Committee, and is likely to be viewed favourably by the CERN Council if sufficient external resources can be found. It could start taking data in 2005.

There is a substantial programme of work for these long-baseline experiments. This includes disappearance experiments, comparing the rates in nearby and far detectors, as planned by K2K and MINOS. Also important are measurements of the neutral-current to charged-current ratio, as also planned by K2K and MINOS. These should provide accurate measurements of  $\Delta m^2$  and  $\sin^2 2\theta$  for  $\nu_\mu \rightarrow \nu_e$  or  $\nu_\mu \rightarrow \nu_s$  oscillations. The K2K experiment is sensitive to about half of the region parameter space suggested by Super-Kamiokande, and MINOS should cover essentially all of it. MINOS should also provide some information on  $\nu_e$  appearance, though it is not optimized for  $e$  detection.

In my personal view, a key measurement will be that of  $\nu_\tau$  appearance via  $\tau$  production. Even if one accumulates many indirect indications that  $\nu_\mu$  oscillate into  $\nu_\tau$ , direct proof is surely essential: "If you have not discovered the body, you have not proven the crime". Remember Jimmy Hoffa: in the absence of a body, it was impossible to prove he had been murdered, let alone who did it. Remember also the gluon: although there were prior indirect arguments, everybody remembers the observation of gluon jets [41] as the

“discovery” of the gluon.

The CERN-NGS beam is being optimized for  $\tau$  production in a far detector [40]. The  $\tau$  event rate  $\propto \sin^2 2\theta (\Delta m^2)^2$ , and should be  $\mathcal{O}(10)$  per year in a kiloton detector if  $\Delta m^2 \sim 3 \times 10^{-3} \text{ eV}^2$  as suggested by the Super-Kamiokande data. As seen in Fig. 8 [40], either OPERA or ICARUS should comfortably be able to detect  $\tau$  production over all the range of  $\sin^2 2\theta$  and  $\Delta m^2$  indicated by Super-Kamiokande, providing closure on the physics of atmospheric neutrinos [42].

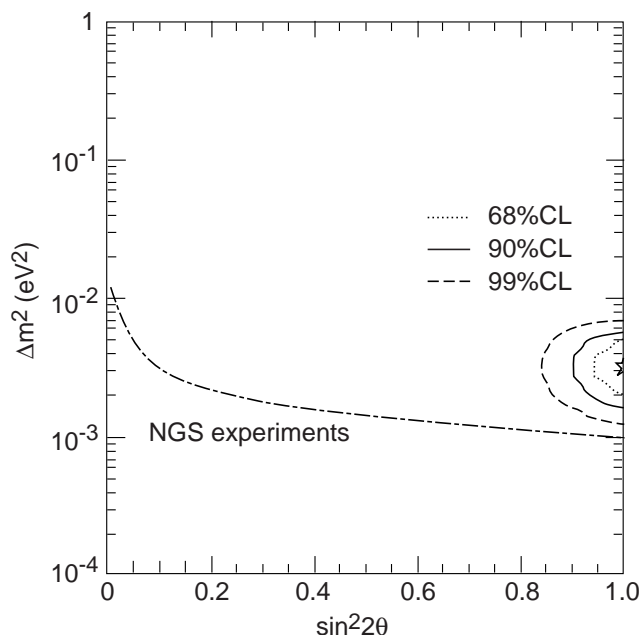


Figure 8. *Possible sensitivity of  $\tau$ -appearance experiments in the proposed CERN-Gran Sasso long-baseline neutrino beam (NGS) [40,42].*

## 6. Possible Future Options

What are the possibilities for the longer-term future? Accelerator options under consideration at CERN and elsewhere include linear  $e^+e^-$  colliders - a first generation with  $\lesssim 1$  TeV in the centre of mass [43], and a possible second generation in the range of 2 to 5 TeV [44] - a  $\mu^+\mu^-$  collider [45,46] - aiming eventually at several TeV in the centre of mass, but with intermediate lower-energy Higgs factory options - and a possible future larger hadron collider with  $\gtrsim 100$  TeV in the centre of mass.

The most relevant option for this talk may be the other physics possibilities of an intense  $\mu$  source. How about stopped- $\mu$  physics with  $\sim 10^{14} \mu \text{ s}^{-1}$ ? The present limits on  $\mu \rightarrow e\gamma$  and  $\mu N \rightarrow eN$  could be improved by many orders of magnitude. Or how about  $\mu N$  scattering with  $\sim 20$  GeV muons on a fixed target: how would this ‘MULFE’ compare with ELFE? Also, the rates for  $\nu N$  scattering with a nearby (polarized?) target ‘NULFE’

would be prodigious. At CERN one could also envisage a  $\mu p$  collider using the LHC beam. However, the most interesting option might be (very-)long-baseline neutrino physics using the neutrinos produced by the decays of stored muons [47], which need not be brought into collision. The  $\mu$ -decay neutrino beams are separated entirely in flavour and charge, have a spectrum that is calculable to high precision, include equal numbers of  $\nu_\mu$  and  $\nu_e$ , and can easily be switched in charge [48].

We have therefore been led to propose a three-step scenario for muon storage rings [46]. The first would be a  $\nu$  *factory*, using  $\mu$ -decay neutrino beams as the “ultimate weapons” for  $\nu$ -oscillation studies. The second step would comprise one or more *Higgs factories*, capable of producing Higgs resonances directly in the  $s$  channel, measuring their total widths, restricting drastically, e.g., the MSSM parameter space, and providing a new window on CP violation in the Higgs sector: the “ultimate weapon” for Higgs studies. The third step could be a *multi-TeV  $\mu^+\mu^-$  collider*. This has advantages over an  $e^+e^-$  collider in the same energy range, provided by its reduced energy spread and its more precise energy calibration. However, the centre-of-mass energy may ultimately be limited by the neutrino-induced radiation hazard[45,49,46].

Any such programme of muon storage rings must face many technical problems related to the proton driver, the target, and capturing produced pions and muons. In addition, muon colliders require a large amount of beam cooling, and the  $\nu$  radiation problem must be addressed before progressing to a high-energy  $\mu^+\mu^-$  collider. However, the physics of the first-step  $\nu$  factory is already very enticing, as we now discuss.

One might envisage  $10^{14}$   $p$  per cycle at a rate of 15 Hz, producing close to  $10^{21}$   $\mu^+(\mu^-)$  per year, leading to  $\nu_\mu + \bar{\nu}_e(\bar{\nu}_\mu + \nu_e)$  beams with fluxes of  $\sim 2 \times 10^{20}$  per year. These fluxes are so large that one could consider very-long-baseline experiments with beams travelling several thousand km [47,48,50,46,51]: Fermilab to Gran Sasso? CERN to Soudan? either or both to Kamioka or Beijing?

The sensitivities to  $\Delta m^2$  and  $\sin^2 2\theta$  of such (very-)long-baseline experiments have recently been studied in [48]. They vary as follows with baseline  $L$  and energy  $E$ :

$$\begin{array}{lll}
 & \textit{appearance} & \textit{disappearance} \\
 \Delta m^2 : & E_\mu^{-1/2} & E_\mu^{-1/4} L^{-1/2} \\
 \sin^2 2\theta : & L E_\mu^{-3/2} & L^{1/2} E_\mu^{-3/4}
 \end{array} \tag{20}$$

As seen here and in Fig. 9, very-long-baseline experiments may actually not confer any benefits for appearance and disappearance studies [48]. However, the long-baseline experiments already offer considerable improvements over the sensitivities of current atmospheric-neutrino experiments. Moreover, as seen in Fig. 10, very-long-baseline experiments may offer a better window on CP-violation effects in  $\nu$ -oscillation studies [48]. Beams from  $\mu$  storage rings could be used to compare  $\nu_\mu \rightarrow \nu_e$  oscillations with the  $T$ -reversed  $\nu_e \rightarrow \nu_\mu$  process as well as the CP-conjugate process  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  (not to mention  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ ). Thus, one may begin to dream of the Holy Grail of  $\nu$ -oscillation studies, the exploration of CP violation in the neutrino sector [52]. This could be connected indirectly with the baryon asymmetry of the Universe via a leptogenesis scenario [53]. It used to be thought that neutrinos could constitute the dark matter: it would be ironic if they gave birth to the visible matter.

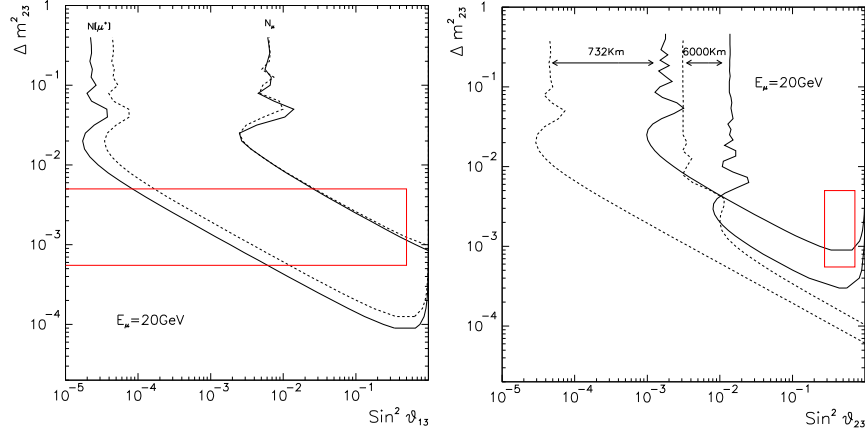


Figure 9. *The sensitivities of long-baseline neutrino experiments using beams from a muon storage ring used as a neutrino factory [48]: (a) to search for mixing between the first- and third-generation neutrinos via appearance (left lines) and disappearance (right lines) for  $\theta_{23} = 45^\circ$  (solid lines) and  $30^\circ$  (dashed lines), assuming a baseline of 732 km, and (b) to search for mixing between the second- and third-generation neutrinos via appearance (dashed lines) and disappearance (solid lines), assuming the indicated beam lengths. The boxes represent current indications and limits.*

## 7. Prospects

Neutrino physics appears finally to be leading particle physics beyond the straitjacket of the Standard Model. The wealth of new data – particularly from Super-Kamiokande [4,6] – is highly suggestive of neutrino masses and oscillations, for both solar and atmospheric neutrinos. In both cases, some definitive experiments are at hand. In the case of solar neutrinos, these include SNO (to see if B neutrinos have oscillated into some other flavour), BOREXINO (to see if Be neutrinos have oscillated strongly), and KamLAND (to test the large-mixing-angle MSW hypothesis using the known flux of reactor neutrinos). Meanwhile, Super-Kamiokande is progressing towards decisive measurements of the spectrum distortion, the day-night effect and the seasonal variation of the solar neutrino flux. In the case of atmospheric neutrinos,  $\pi^0$  production and the zenith-angle distribution may soon provide decisive discrimination between the  $\nu_\mu \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_s$  scenarios. In this case, the definitive measurements will be made by long-baseline neutrino beams from accelerators, starting with K2K. These have an extensive programme of work ahead of them, including measurements of  $\nu_\mu$  disappearance and the neutral current/charged current ratio, as well as  $\nu_e$  and  $\nu_\tau$  appearance experiments. The detailed measurements possible with controlled accelerator beams will dissipate any remaining doubts about the interpretation of the atmospheric neutrino experiments.

In the longer run, the concept of a neutrino factory based on a muon storage ring offers the prospect of a complete set of oscillation measurements with separated neutrino flavours and charges, including the possibility of very-long-baseline experiments and a

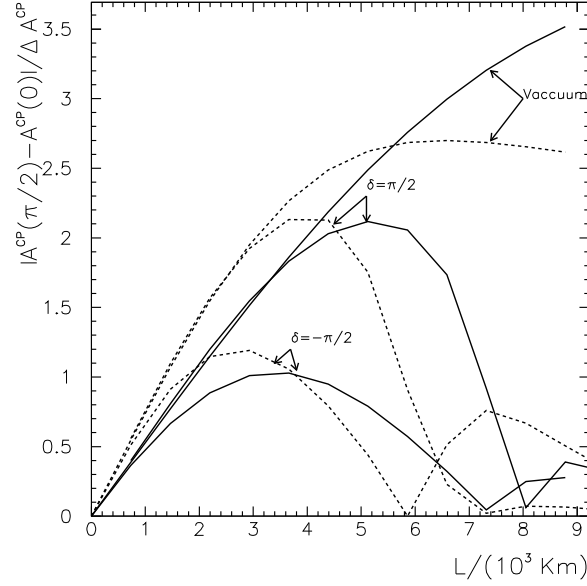


Figure 10. *Sensitivity of (very-)long-baseline experiments to CP violating effects in neutrino oscillations [48].*

quest for CP violation. This option also offers other exciting opportunities in  $\mu$  and  $\nu$  physics, as well as serving as a stepping-stone towards Higgs factories and a high-energy  $\mu^+\mu^-$  collider. As never before, neutrino physics is entering, and perhaps diverting, the mainstream of particle physics.

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